Development Program of Innovative Reactor Systems in the World

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OUTLINE

SOME PERSPECTIVES FOR SUSTAINABLE NUCLEAR ENERGY ?

PRESENT STATUS AND PROJECTIONS WITH THE 3rd GENERATION

WHY A NEW GENERATION OF NUCLEAR REACTORS IS NEEDED ?

THE GENERATION IV INTERNATIONAL FORUM

THE STRATEGY IN FRANCE AND EUROPE

R&D ISSUES AND HIGHLIGHTS:
  FAST NEUTRON SYSTEMS AND CLOSED FUEL CYCLE
  HIGH TEMPERATURE REACTORS AND APPLICATIONS

TOOLS, INFRASTRUCTURES, EDUCATION & TRAINING
Sustainable energy development scenario (IEA - 2003)

Many published scenarios predict a significant increase of the share of nuclear in the energy mix by 2050.

Installed nuclear power increased by a factor 3-5 by 2050?
SOME PERSPECTIVES FOR SUSTAINABLE NUCLEAR ENERGY?

Assets of nuclear power

- Economic competitiveness
  ~ 28 vs 36 €/MWh (gas, coal)
  [DGEMP-DIDEME Study 2003]

- High safety level and steady improvements

- Energy security

- Escalating price of oil

Green-house gas emissions from electricity

Dispersion due to various technologies

Quasi no CO₂ emission with nuclear

Generations of Nuclear Power Systems

- 1st generation DISMANTLING
  UNGG
  Magnox

- 2nd generation OPERATION
  REP 900
  REP 1300
  N4 (1450)

- 3rd generation OPTIMIZATION
  EPR (1600), AP1000,
  ABWR, ESBWR

- 4th generation DESIGN and R&D
  Prototypes 2020-25
  DIAMEX/SANEX, GANEX
PRESENT STATUS AND PROJECTIONS WITH THE 3rd GENERATION

EPR: European Pressurized Reactor

**PWR 1600 MWe, 60 years, \( K_D \sim 91\% \)**

![EPR Flamanville (2012)](image1)

![EPR Olkiluoto (2011)](image2)

- Core melt spreading area
- Double-wall containment with ventilation and filtration system
- Containment heat removal system
- Four-train redundancy for main safeguard systems
- Inner refueling water storage tank
- Reinforced safety features and economic competitiveness

PRESENT STATUS AND PROJECTIONS WITH THE 3rd GENERATION

**Advanced BWRs: GE ABWR and ESBWR**

- ABWR (~1300 MWe)
- SBWR (670 MWe)
- ESBWR (~1500 MWe)
**WHY A NEW GENERATION OF NUCLEAR REACTORS IS NEEDED?**

Minimizing waste with advanced actinide recycling

- Plutonium has a high energetic potential
- Plutonium is the major contributor to the long term radiotoxicity of spent fuel

→ **Plutonium recycling**

- After plutonium, MA (Am, Cm, Np) have the major impact to the long term radiotoxicity

→ **MA transmutation**

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**WHY A NEW GENERATION OF NUCLEAR REACTORS IS NEEDED?**

- Some countries (USA, Sweden, Finland) have made the choice of « open cycle ».
  
  No fuel processing, nuclear spent fuel stored into repository
  
  → Valuable materials U et Pu are lost, the potential radiotoxicity and the volume of nuclear waste to repository is significant.

- In France, spent fuel is recycled.
  
  U and Pu are recovered, stored and used (partially) for fresh fuel fabrication.
  
  Fuel treatment and recycling save Unat and minimize the volume and radiotoxicity of nuclear waste.

Japan is promoting the same strategy
**WHY A NEW GENERATION OF NUCLEAR REACTORS IS NEEDED?**

Uranium demand is larger than natural uranium production

→ Complementary resources have been engaged (Pu, recycled U, MOX)

Annual production of uranium and needs for nuclear reactors (1945-2003)

If nuclear energy grows significantly, uranium supplies could be engaged by 2050

(source NEA, 2006)

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**WHY A NEW GENERATION OF NUCLEAR REACTORS IS NEEDED?**

Open fuel cycle in LWRs

Utilization of uranium ore for 1 GWe x year

\[ \begin{align*}
200 \text{ tons } U_{\text{nat}} & \quad E \quad 20 \text{ tons } U_{5\%} \quad R \quad 180 \text{ tons } U_{\text{dep}} \\
99.3\% & 238U \quad + \quad 0.7\% & 235U
\end{align*} \]

Fast neutron reactors need only 1 ton U238 (U_{\text{dep}} & U_{\text{rep}}) that is converted into plutonium and burned in situ (regeneration → breeding of fissile fuel)

→ \( U_{\text{dep}} \) generated by a LWR over a 50 year lifetime is worth > 5000 years of the same power output with fast reactors
Why a New Generation of Nuclear Reactors Is Needed?

Why should we do better than the 3rd generation?...

- The large scale development of 3rd generation reactors challenges uranium resources: identified conventional resources (at a cost < 130 $/kg) represent 160 years of today’s consumption (only about 0.5% of natural uranium is used)
- The management of nuclear wastes will have to be further improved
- Having in mind a perspective of fossil fuel shortage, nuclear technology should get prepared to answer other needs than electricity supply: hydrogen, process heat, desalination,…
- Larger spreading of nuclear power needs proliferation resistance

New types of nuclear reactors must be designed in order to ensure energy supply in a context of sustainable development

Fast neutron reactors have the best capability for breeding and transmutation

<table>
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<tr>
<th>isotopes</th>
<th>Thermal</th>
<th>Fast</th>
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<tr>
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<tr>
<td>$^{236}\text{U}$</td>
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<tr>
<td>$^{245}\text{Cm}$</td>
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</table>

Conditions for breeding… more precisely

\[ N_\alpha = \nu - 2(1 + \alpha) \]

\[ N_\alpha > 0 \rightarrow \eta > 2 \]

The ratio \( \alpha = \text{capture/fission} \) is favourable to MA fission in fast neutron spectrum
Scenario for the renewal of nuclear reactors in France and in Japan

**Major role of LWRs over the 21st century...**

- Replacement staggered over a 30-year period (2020 - 2050)
- Rate of construction: 2,000 MW/year

**Generation 3+**

- Existing fleet: 40-year plant life
- Plant life extension beyond 40 years

**Generation 4**

- Fast Reactors
- 58 PWRs (20 MOX)
- 63.2 GWe

**...Transition from PWRs to Gen IV fast neutron systems by 2035**

**Japan – Total capacity of ~58 GWe after 2030**

- **LWR (UO₂ fuel)**
- **LWR (MOX fuel)**
- **FBR (BR. 1.1)**
- **FBR (BR. 1.03)**

**Closed fuel cycle is an industrial reality in France and in Japan**

- **Rokkasho reprocessing plant**

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**The GNEP initiative**

The recognition of the benefit of treatment/recycling strategies

- Expand use of nuclear power
- Minimize nuclear waste
- Demonstrate recycle technology
- Demonstrate Advanced Burner Reactors
- Establish reliable fuel services
- Demonstrate small, exportable reactors
- Enhanced nuclear safeguards technology

G. Bush, January 2006

A renewed vision of nuclear fuel cycle in USA ➔ Major change in the Carter doctrine with regards to fuel reprocessing
A considerable feedback on fast neutron reactors...

...in Japan

The choice of the loop-type design

Superphenix (Creys-Malville)

Phenix (Marcoule)

Joyo (50 MWt)

Monju (280 MWe)
(shutdown in 1995, to be restarted in 2008)

Superphenix: an industrial prototype (1200 MWe), shutdown in 1998

India and China are building Sodium Fast Reactors...

PBFR (India)
500 MWe (2010)

CEFR (China)
65 MWt, 20 MWe (2010)

...The construction of BN 800 has been initiated in Russia
Forum Generation IV: towards sustainable nuclear energy

Nuclear is a CO₂-free option for sustainable energy

New requirements for sustainable nuclear energy

Search innovative solutions for:
- Waste minimisation
- Natural resources conservation
- Proliferation resistance

Perform continuous progress on:
- Competitiveness
- Safety and reliability

Develop the potential for new applications:
- hydrogen, syn-fuels, desalinated water, process heat

⇒ Systems marketable from 2040 onwards

THE GENERATION IV INTERNATIONAL FORUM

GIF selection of 6 nuclear systems

- Sodium Fast Reactor
- Lead Fast Reactor
- Gas Fast Reactor
- Very High Temperature Reactor
- Super Critical Water Reactor
- Molten Salt Reactor

The recognition of the major potential of fast neutron systems with closed fuel cycle for breeding (fissil regeneration) and waste minimization (minor actinide burning)
Interest shown by GIF members for each of the 6 concepts

Update on Participation in System Arrangements (status July 2007)

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<th>LFR(a)</th>
<th>MSR(a)</th>
<th>SCWR</th>
<th>SFR</th>
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<td>X</td>
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<tr>
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<td>2</td>
<td>2</td>
<td>4</td>
<td>7</td>
<td></td>
<td>8</td>
</tr>
</tbody>
</table>

a: SA not yet negotiated
b: Not yet acceded to Framework Agreement
INPRO Methodology
A concrete achievement of INPRO phase 1, to be further assessed and improved during phase 2

THE STRATEGY IN FRANCE AND EUROPE
R&D Strategy of France for Future Nuclear Systems

Approved by the Ministries of Research and Industry on March 17, 2005

1 - Development of Fast Reactors with a closed fuel cycle:
- Sodium Fast Reactor (SFR)
- Gas Fast Reactor (GFR)
- New processes for spent fuel treatment and recycling

2 - Nuclear hydrogen production and high temperature process heat supply to the industry:
- Very High Temperature Reactor (VHTR)
- Water splitting processes for hydrogen, synthesis of hydrocarbon fuels, process heat...

3 - Innovations for LWRs (Fuel, Systems...)

Sodium Fast Reactor
Gas Fast Reactor
Very High Temperature Reactor
THE STRATEGY IN FRANCE AND EUROPE

Sustainable Nuclear Energy Technology Platform (SNE-TP)

Objectives & organization: 3 main areas

The involvement of industry and safety organizations together with research institutes and universities

Draft Strategic Research Agenda (SRA) to be issued end 2008

THE STRATEGY IN FRANCE AND EUROPE

In the French strategy, 2 options of fast reactors are examined concurrently

- **A reference option**: the Sodium Fast Reactor (SFR)
  - Considerable experience world-wide
  - **The most mature of Fast Reactor concepts**
  - Major improvements are sought with respect to SPX and EFR

- **An alternative**, the Gas Fast Reactor (GFR)
  - Attractive features such as transparent and inert coolant
  - Capable of reaching high temperatures (sustainable version of VHTR)
  - **Requires some technological breakthroughs, but provides access to both a fast neutron spectrum and high temperatures**
Competitive economics relative to Gen III LWRs
- Reduction of *investment cost* (design simplification, increased compactness)
- Optimization of *operation* in order to alleviate possible constraints associated with a metallic coolant (in-service inspection, maintenance, repair)

Enhanced safety
- Decrease or suppression of *risks of sodium/water interaction*
- Practical exclusion of large energy release in case of *severe accidents* (reactivity effects, reliability of passive systems)

Closure of the fuel cycle
- U/Pu closed cycle
- Flexible strategy for MA transmutation (← homogeneous, heterogeneous →)

**R&D ISSUES AND HIGHLIGHTS: A NEW GENERATION OF SFR**

- Large diameter pins
- High burn up (dose > 200 dpa) → clad without swelling

Swelling of advanced austenitic steels and ferrito-martensitic steels used as fuel cladding in Phenix

**SFR V2**
83.4% Dth

Advanced fuel cladding: 316 Ti → 15-15 Ti → F/M ODS
### Potential of progress with dense ceramics

<table>
<thead>
<tr>
<th>Pu/(U+Pu) = 0.2</th>
<th>Carbide (U,Pu)C</th>
<th>Nitride (U,Pu)N</th>
<th>Oxide (U,Pu)O₂</th>
<th>Metal (U,Pu)Zr</th>
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</thead>
<tbody>
<tr>
<td>Heavy atoms density (g/cm³)</td>
<td>12.95</td>
<td>13.53</td>
<td>9.75</td>
<td>14</td>
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<tr>
<td>Melting point (°C)</td>
<td>2420</td>
<td>2780</td>
<td>2750</td>
<td>1080</td>
</tr>
<tr>
<td>Thermal conductivity (W/m/K)</td>
<td>16.5</td>
<td>14.3</td>
<td>2.9</td>
<td>14</td>
</tr>
</tbody>
</table>

Carbide (and nitride) have an increased margin to melting which can benefit:
- either to increase power density (economy, HM inventory)
- or to improve safety (accident prevention)

### A strategy for severe accident management

Provisions for mitigating the core melting risk and, in the event of a core meltdown, for preventing high-energy accident sequences:

- Simulation of BTI* in Phénix (SIMMER-III code)

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*BTI: Total Instantaneous Blockage of a fuel assembly
R&D ISSUES AND HIGHLIGHTS: A NEW GENERATION OF SFR

Several options under investigation for energy conversion

- **Gas cycle conversion** (N₂, supercritical CO₂)
- **Water/steam (Rankine cycle)**
  - Simplification of intermediate circuit and avoidance of sodium/water interaction

**SG-HX unit, 600 MW**
Na/Pb-Bi/H₂O
Φ~4m X h~11m

« Ultra-compact »
3-fluid component (SG-HX)

Intermediate circuit design
(sodium / X / water)

SG materials for T°> 550°C

Pressure optimization

Pool or Loop ?

- **Large pool-type concept** (1500 MWe)
- **Design optimisations**
  - core vessel diameter reduced by ~ 30% compared to EFR (17 m)
- **3 compact intermediate loops**

**Modular concept** (500 MWe) with gas conversion system (no intermediate circuit)

- Transportable core vessel (~ 7 m)
- Nitrogen energy conversion system (2 loops), sodium/nitrogen heat exchanger
- Core outlet temperature > 600 °C
**R&D Issues and Highlights: Towards Closed Fuel Cycle**

**Fast neutron reactor closed fuel cycle: several options**

- **Homogeneous recycling (Gen IV)**
- **Heterogeneous recycling**
- **Recycling U Pu only**

All options should be kept available, they could be used in a sequence.

**X-ray micrography of MOX microstructure**

**Grouped actinide partitioning and refabrication (SFR & GFR)**

**GANEX flow-sheet**
**R&D Issues and Highlights: A New Generation of SFR**

**A SFR prototype under operation by 2020**

1. **Electricity producer prototype (power range 250-600 MWe)**
   to demonstrate the promising technologies for the commercial SFR (including ECS, ISIR, ...); size choice will be the result of an optimization/compromise between costs, risks and representativity.

2. **Convincing demonstration of the improvements proposed against the weak points of past SFRs**

3. **Resources saving**: operation with recycled materials, while reinforcing safety and proliferation resistance.

4. **Waste management**: progressive evaluation and demonstration of Minor Actinides recycling.

5. **Need for associated fuel cycle facilities**: MOX fuel for the starting core and irradiation capabilities at the fuel S/A level (advanced fuels, MAs bearing fuels).

**Harmonisation of prototypes**

France, Japan and USA plan SFR prototypes by 2020-2025

- **French prototype**
- **Japanese prototype (JSFR)**
- **American prototype (ARR)**

An approach aiming at international harmonisation is underway:
- Assure complementarity of prototypes (objectives, options,...)
- Optimize related infrastructures (including fuel fabrication facilities)
R&D ISSUES AND HIGHLIGHTS: GFR AS PROMISING ALTERNATIVE

**SFR**

- The reference option (significant past experience and innovation objectives)
  - Reduction of investment cost
  - Safety level comparable to 3rd generation LWRs
  - Improved operation techniques (ISIR, ...)

**GFR**

An alternative track based on:
- Benefits from helium as a coolant
- Robust fuel (including severe accident conditions)
- Potential for high temperature applications

A common concern: the potential for integral recycling of actinides

Milestone 2020: prototype (250-600 MWe)

Milestone 2020: experimental reactor (ALLEGRO, 50-70 MWt)

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R&D ISSUES AND HIGHLIGHTS: GFR AS PROMISING ALTERNATIVE

**A first consistent design for a 2400 MWt GFR**

- Robust decay heat removal strategy (passive after 24hrs)
- GFR preliminary feasibility report issued January 2008

- Innovative fuel

GFR 2400 MWt (1100 MWe) reference concept

ALLEGRO (50-70 MWt)
Analysis of GFR fast depressurization accident

Efficiency of DHR systems and control of fuel temperature < 1600°C

- 24 hr in forced convection (small pumping power ~ 10 kWe)
- For longer term, natural circulation at 1.0 MPa

GFR innovative fuel concept

**Axial gap**: closed at beginning of life (BOL) for homogeneous thermal behaviour

**Radial gap**: retention of fission gases and helium, closure at end of life (EOL)

Behaviour under irradiation (FUTURIX in Phenix, IRRDEMO in BR2)
**R&D Issues and Highlights: V/HTR and High T° Applications**

### ANTARES Concept

**ANTARES**
- **PROJECT**
- **ANTARES**

**Concept**
- **(600 MWt, 850°C)**

**The interest to VHTR is essentially driven by its potential for a large scope of process heat applications**

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**R&D Issues and Highlights: V/HTR and High T° Applications**

**HTR/VHTR: the R&D Challenges**

1. **Manufacturing of particle fuel**
   - Requirement on kernel sphericity \( \Phi_{\text{max}} / \Phi_{\text{min}} \)
   - Fulfilled at 90% (November 2007)
   - \( \text{UO}_2 \) **TRISO** particles (natural uranium)
   - Fabricated in **GAIA** (Cadarache)

2. **High temperature gas-gas IHX and materials**
   - Different plate concepts appear as good candidate technologies
   - **Plate Stamped Heat Exchanger (PSHE)**
     - Temperature ~ 850°C

3. **Helium technology**
   - Development and qualification of helium technology and components
   - **Helium circulator**
   - **Helium purification**
     - **(CIGNE)**
   - **Helium Technology Platform** (Cadarache)
   - **HELITE loop** (in project)
R&D ISSUES AND HIGHLIGHTS: V/HTR AND HIGH T° APPLICATIONS

Hydrogen production: thermo-chemical cycles (Sulfur/Iodine)

- Basic measurements for data acquisition
- Flow-sheet optimization
- Chemical engineering

A 80 000 m³/hr S/I production plant

200 l/hr S/I micro-pilot

Components design
- Plant safety
- Cost estimates

R&D ISSUES AND HIGHLIGHTS: V/HTR AND HIGH T° APPLICATIONS

in cooperation with

ArcelorMittal

Coupling of a nuclear reactor (VHTR) with steel factory (iron pre-reduction)

⇒ A low CO₂ steelmaking route with possible CO₂ recovery

A VHTR (600 MWt) operated in cogeneration can feed a pre-reduction unit producing 6000 tons / day of pre-reduced iron (~ 2 standard units)
R&D ISSUES AND HIGHLIGHTS: V/HTR AND HIGH T° APPLICATIONS

NGNP: Next Generation Nuclear Plant (US DOE)

- Enables commercialization of High Temperature Gas-Cooled Reactor technology to provide process heat
- Completed pre-conceptual design studies for 3 different vendor concepts led by Areva NP, GA and Westinghouse (operation planned 2018)

Computational tools for current and future nuclear systems

- Multi-physics, multi-scale modelling
  - Core physics (APOLLO 3)
  - Thermal-hydraulics (NEPTUNE)
  - Fuel behaviour (PLEIADES)
  - Joint development of numerical platforms (CEA-EDF-AREVA)
Research Reactors
- OSIRIS, ORPHEE, HFR, LVR-15...
- PHEBUS, CABRI
- EOLE, MINERVE, MASURCA

Hot labs
- LECI
- PE-LECI
- LECA-STAR
- ATALANTE...

JHR (Jules Horowitz Reactor): a new MTR by 2014 in Cadarache

International partnership
- CEA, EDF, AREVA
- EU, Belgium, Czech Republic, Finland, Spain, India, Japan, Sweden...

Master in Nuclear Engineering

Objectives:
- Education of Engineers and Researchers / multidisciplinary skills / thorough knowledges in nuclear reactor field

Careers Opportunities:
- Engineer in nuclear industry
- Researcher, Teacher / universities, research centers

Main Educational Topics:
- Nuclear Physics
- Reactor Physics / Particle Propagation
- Thermal Hydraulics
- Nuclear Materials
- Modelling and calculation codes
- Nuclear Reactor Design and Operation / Reactor lines
- Nuclear Power Cycles
- Safety / Criticality
- Protection / Radiation shielding
- 5 months training in industrial company / in research laboratory

Admission Prerequisites:
- This master M2 appeals to students of M1 in Nuclear Engineering
- Master 2 or equivalent
- Demoned to international candidates
- Contract granted on written academic file

Master in Nuclear Engineering

Training courses & technical visits

Doctoral school

VISITS
- Fuel fabrication plant (FBFC – FRAMATOME AMF)
- Uranium refining and conversion plant (COMBERHED)
- Uranium enrichment plant (EURISOR)
- MOX fuel fabrication plant (MELOX)
- Re – PAN (RAWEC)
- La Hague spent fuel reprocessing plant (COSEMA)
- Storage site for low radioactivity waste (ANDRA)
A clear trend towards a global vision of energy production and waste management, involving the need of nuclear technologies preserving uranium resources and minimizing nuclear wastes.

The recognition of the essential role of fast neutron systems with closed cycle technologies. SFR considered the reference option in many countries (France, Japan, USA, Europe,...), with regard to considerable past experience. GFR and LFR are evaluated as alternative options in Europe.

Market opportunities envisioned for cogeneration applications (H₂, synfuels, steel fabrication,...). HTR/VHTR offer the best potential.

International cooperation on future nuclear systems (Gen IV, INPRO...). Harmonization of the approach at international level (innovation R&D, simulation tools, infrastructures, prototypes).

Training a young generation of scientists in nuclear engineering